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Case Study: Sensitivity Analysis of the Barataria Basin Barrier Shoreline Wetland Value Assessment Model[1]

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OVERVIEW: Sensitivity analysis is a technique for systematically changing parameters in a model to determine the effects of such changes on model outcomes (Schmolke et al. 2010). It is an essential tool for model building and quality assurance. Sensitivity analysis also compliments uncertainty analysis because sensitivity analysis orders input importance by determining variation in output and by identifying important response thresholds. This technical note provides an example application of sensitivity analysis in support of ecosystem restoration planning. It is intended to supplement other publications about Environmental Benefits Analysis (EBA) that discuss a broader array of sensitivity techniques and applications. In this instance, the application of sensitivity analysis addresses the relevance of questions posed during an Independent External Peer Review (IEPR).

BARATARIA BASIN BARRIER SHORELINE (BBBS) STUDY: On average, Louisiana's coastal marshes are receding at alarming rates – over 27 mi^2/yr – due to a number of factors, including: sea level rise, river-marsh disconnection, local consolidation and subsidence, and coastal erosion (Barras et al. 2008). These coastal systems provide numerous ecosystem goods and services, including fish and wildlife production, storm damage reduction, and recreation. Federal, state, and local partners have jointly pursued large-scale restoration projects to reduce marsh loss and maintain these wetlands as healthy functioning ecosystems. The Barataria Basin Barrier Shoreline (BBBS) restoration project was identified through the Louisiana Coastal Area (LCA) program as critical to maintaining the Caminada Headland and Shell Island reaches of the Gulf shoreline to prevent larger scale, potentially irreversible ecosystem impacts.

Large-scale ecosystem restoration projects require extensive planning and analysis prior to implementation to ensure the most effective alternatives are selected. Alternatives are compared on the basis of forecasted "benefits" of restoration determined using numerical models such as the commonly applied Habitat Evaluation Procedures (HEP). HEP combines habitat quantity (e.g., acres) with an assessment of habitat quality scored from zero to one, a Habitat Suitability Index (HSI). This index is determined from measured data or professional judgment, and is generally represented as a "habitat suitability curve" that assigns a quality score to a range of values for a given parameter. HEP was originally developed for individual species, and suitability curves were developed to capture environmental tolerances of the focal species (USFWS 1981). Since

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ecosystem management and restoration rarely centers on optimizing habitat for a single species, more recent HEP models have focused on ecological communities rather than specific taxa (e.g., Gulf Coast salt marsh ecosystems; EWG 2006). For these models (e.g., Wetland Value Assessment), the HSI represents an aggregation of multiple habitat suitability curves covering a variety of parameters describing ecosystem structure or process.

Wetland Value Assessment. Based on its quantitative nature and historical application in the region, the Wetland Value Assessment (WVA) was selected as an appropriate model for assessing the relative merits of BBBS alternatives. WVA was developed by an interdisciplinary and inter-agency team of scientists specifically for determining suitability of coastal wetlands in providing resting, foraging, breeding, and nursery habitat to a diverse assemblage of fish and wildlife species in coastal Louisiana (EWG 2006). Strictly speaking, WVA is not a single model, but rather a procedure that applies a family of models addressing seven ecological communities of the region: (1) fresh/intermediate marsh; (2) brackish marsh; (3) saline marsh; (4) barrier island; (5) barrier headland; (6) swamp; and (7) coastal chenier/ridge. WVA is a HEP-type approach whereby habitat quality, or suitability, is correlated to relevant components of ecosystem structure on a zero to one scale. For instance, in the WVA saline marsh model, suitability is assumed to vary linearly from 0.1 to 1.0 as the percentage of marsh area with emergent vegetation increases (Figure 1a). Each of these "suitability index curves" is then combined into a composite habitat suitability index (HSI) through a specific aggregation algorithm which is then multiplied by the quantity of habitat, in acres, to obtain the number of "habitat units" (HU) provided by a given alternative. Whereas traditional HEP models focused on specific taxa, WVA assesses the fish and wildlife community collectively.

For each alternative, WVA quantifies changes in habitat quality. The results are combined with habitat quantity estimates and costs to compare the effectiveness of different alternatives. Because WVA outputs (HUs) are snapshots of conditions at a given time, benefits must be assessed at several points over the project life (50 years) then annualized to provide a consistent metric in the form of average annual habitat units (AAHUs). In addition, the basis for assessing benefits of a restoration project is not the number of habitat units provided by an alternative, but the improvement the alternative provides over a baseline condition, which is the future condition of the site without the proposed restoration. Thus, net benefits are the difference in AAHUs provided by the alternative and the future without project (FWOP) condition (i.e., $AAHU_{net} = AAHU_{alternative} - AAHU_{FWOP}$; USACE 2009).

Model Certification. The USACE requires that planning models be reviewed for technical and system quality and usability. The purpose of model review is to ensure the scientific validity and technical quality of tools used for planning, and to ensure the tools conform to policy and usability requirements (USACE 2005, USACE 2007). WVA models were evaluated in accordance with EC 1105-2-412 (Assuring Quality of Planning Models, USACE 2011). Review of the WVA model identified two concerns associated with model construct (BMI 2009):

Comment 1. Starting the SI curves for all variables at 0.1 is problematic because even habitat with no ecological value appears to have some ecological value.

Comment 18. The use of the geometric mean may be more appropriate than the arithmetic mean to derive some HSIs. Provide scientific basis for the decision to use one over the other.

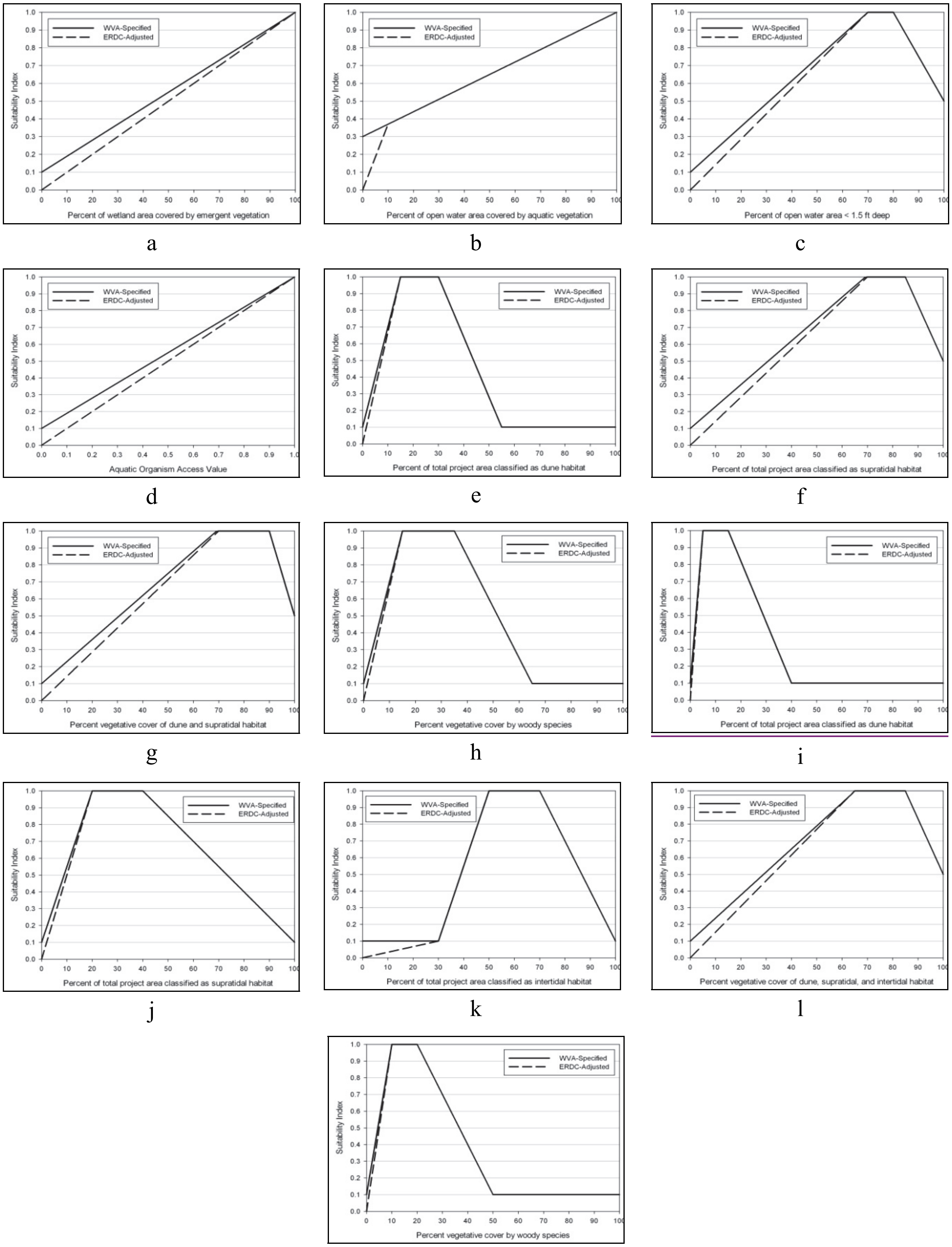

Figure 1. Suitability index curves as specified by WVA (solid lines) and adjusted by ERDC (dashed lines) to address review comments. (a-d) saline marsh (SIV_1, SIV_2, SIV_4, SIV_6); (e-h) barrier headland (SIV_1, SIV_2, SIV_3, SIV_4); and (i-m) barrier island (SIV_1, SIV_2, SIV_3, SIV_4, SIV_5).

SENSITIVITY ANALYSIS: Regardless of purpose or function, all models are limited by scientific understanding of the process being modeled, validity of input parameters, and ability of the model structure to capture understood processes (Schmolke et al. 2010, Schultz et al. 2010). As such, there is value in examining the sensitivity of a model to changes in one or all of these factors and how that sensitivity alters conclusions. For BBBS, the WVA model was selected based on time, funding, and resource availability, among other factors. Given that each WVA sub-model (e.g., saline marsh) has several input parameters (usually 5-7) which are assessed for multiple times (at least: year 0, year 1, year 20, and year 50) and multiple alternatives, comprehensive examination of input uncertainty would be a prohibitively large task beyond the scope of the review comments. Herein, the authors apply sensitivity analysis to the WVA to examine the influence of model structure on restoration decision making. The analysis examines two components of model structure: 1) the influence of suitability curve boundary conditions and 2) the influence of aggregation techniques for combining suitability curves into a Habitat Suitability Index (HSI). WVA model sensitivity was examined specifically for relative comparison of alternatives in the Barataria Basin Barrier Shoreline restoration project by examining the influences of boundary conditions and aggregation methods on conclusions reached in the BBBS restoration study. Although seven WVA sub-models exist, only the WVA sub-models applied to the BBBS study were addressed: saline marsh with both emergent and open water components (EWG 2007), barrier headlands (EWG 2002a), and barrier islands (EWG 2002b).

Boundary Conditions. Each of the WVA sub-models specifies a set of parameters that influence marsh community health (Table 1) and identifies a relationship between each of these parameters and habitat suitability for the community. These relationships are presented as graphs of functions (e.g., for Figure 1a, $SalineSIV_1 = 0.009 * \%_{emergentveg} + 0.1$), as well as constructed scales or tables (e.g., Saline Marsh SIV_3 is a scale for marsh connectivity that provides users with a suitability index based on photographs of reference marshes). In these models, some suitability curves have non-zero y-intercepts indicating that some value always exists for fish and wildlife. Model reviewers expressed concern that HSI values should always approach zero to indicate that quality is insufficient for the community as a whole and is only providing habitat for a few species under these conditions (i.e., Comment 1, BMI 2009).

Table 1. Suitability index parameters of relevant WVA sub-models.

Suitability Index	Saline Marsh	Barrier Headland	Barrier Island
SIV_1	Percent of wetland area covered by emergent vegetation	Percent of area classified as dune	Percent of area classified as dune
SIV_2	Percent of open water area covered by emergent vegetation	Percent of area classified as supratidal	Percent of area classified as supratidal
SIV_3	Marsh edge and interspersion	Percent of vegetative cover of dune and supratidal habitat	Percent of area classified as intertidal
SIV_4	Percent of open water < 1.5 ft deep relative to marsh surface	Percent vegetative cover by woody species	Percent vegetative cover of dune, supratidal, and intertidal habitat
SIV_5	Average annual salinity	Beach/surf zone features	Percent vegetative cover by woody species
SIV_6	Aquatic organism access	n/a	Edge and interspersion
SIV_7	n/a	n/a	Beach/surf zone features

The sensitivity of the three WVA models was tested to adjustments in the suitability curve intercepts. The situation in which all intercepts are as specified in WVA model documentation (EWG 2002a, 2002b, 2006, 2007) was compared with one in which the suitability index curves are forced through a near-zero intercept (explained in greater detail below). Figure 1 shows the WVA-specified and zero-intercept suitability index curves that were assessed. It is important to note that not all WVA parameters were evaluated in this manner; some suitability relations are pictorial or categorical and the zero-intercept concerns do not apply, while some relations provide for maximum suitability at zero values (i.e., *SIV* = 1 at parameter = 0). The two assessed scenarios reflect maximum model sensitivity to this type of structural change.

Aggregation Methods. Suitability indices are combined in numerous ways to generate the composite HSI (see USFWS 1981 for guidelines on HSI development). For instance, model components can be aggregated through arithmetic, geometric, or harmonic means (Equation 1 a, b, & c, respectively), nested averages (e.g., Equation 1d), or hybridized versions of each (e.g., Equation 1e), all of which may be valid approaches. The aggregation algorithms used for WVA are discussed in the model documentation (EWG 2002a, 2002b, 2006, 2007). The approach was to evaluate changes in model outcomes using four alternative aggregation techniques: (1) the WVA-specified formula which contains weighting factors; (2) a geometric mean without weighting factors; (3) an arithmetic mean without weighting factors; and (4) a harmonic mean without weighting factors (Table 2). The arithmetic, geometric, and harmonic averaging methods do not capture the relative importance of parameters as they were developed for WVA. However, these scenarios provide a relative comparison of aggregation algorithms and the sensitivity of the model to these options.

$$\text{(a)}\quad \bar{x} = \frac{x_1 + x_2 + x_3}{3} \qquad \text{(b)}\quad \bar{x} = \sqrt[3]{x_1 x_2 x_3} \qquad \text{(c)}\quad \bar{x} = \frac{3}{\frac{1}{x_1} + \frac{1}{x_2} + \frac{1}{x_3}}$$

$$\text{(d)}\quad \bar{x} = \frac{x_1 + \left(\frac{x_2 + x_3}{2}\right)}{2} \qquad \text{(e)}\quad \bar{x} = \frac{x_1 + \sqrt{x_2 x_3}}{2} \tag{1}$$

Due to complications arising from zero values input to these aggregation schemes, an intercept of 10^{-10} was used. This value was deemed sufficiently small to test the influence of zero-intercepts while maintaining numerical continuity. The figure was chosen by averaging quantities of seven, five, and three variables with one small value (e.g., 0.001) and the rest equal to one using arithmetic, geometric, and harmonic means. The motivation behind suggesting alternative aggregation methods is that geometric and harmonic means will more accurately reflect limiting factors in the analyses; therefore, the authors wanted to test how small a value had to be to become a “limiting factor” which was assumed to be $HSI_{combined} < 0.05$ (Figure 2). These near-zero intercepts will be referred to as the zero-intercept condition.

Test Matrix. In order to test sensitivity to changes in both boundary conditions (i.e., intercepts) and aggregation techniques, the authors examined all possible combinations of the two conditions as shown in Table 3, and will refer to these tests as indicated in the table.

Table 2. Aggregation formulae used in analyses.

Aggregation Technique[1]	Saline: Emergent Marsh	Saline: Open Water	Barrier Headland	Barrier Isand
WVA Specified	$\dfrac{3.5\sqrt[4]{SIV_1{}^3 SIV_6} + \dfrac{SIV_3 + SIV_5}{2}}{4.5}$	$\dfrac{3.5\sqrt[7]{SIV_2{}^2 SIV_6{}^5} + \dfrac{SIV_3 + SIV_4 + SIV_5}{3}}{4.5}$	$0.23SIV_1 + 0.23SIV_2 + 0.18SIV_3 + 0.18SIV_4 + 0.18SIV_5$	$0.14SIV_1 + 0.14SIV_2 + 0.17SIV_3 + 0.20SIV_4 + 0.10SIV_5 + 0.15SIV_6 + 0.10SIV_7$
Geometric Mean	$\sqrt[4]{SIV_1 SIV_3 SIV_5 SIV_6}$	$\sqrt[5]{SIV_2 SIV_3 \ldots SIV_6}$	$\sqrt[5]{SIV_1 SIV_2 \ldots SIV_5}$	$\sqrt[7]{SIV_1 SIV_2 \ldots SIV_7}$
Arithmetic Mean	$\dfrac{SIV_1 + SIV_3 + SIV_5 + SIV_6}{4}$	$\dfrac{SIV_2 + SIV_3 + \ldots + SIV_6}{5}$	$\dfrac{SIV_1 + SIV_2 + \ldots + SIV_5}{5}$	$\dfrac{SIV_1 + SIV_2 + \ldots + SIV_7}{7}$
Harmonic Mean	$\dfrac{4}{\frac{1}{SIV_1} + \frac{1}{SIV_3} + \frac{1}{SIV_5} + \frac{1}{SIV_6}}$	$\dfrac{5}{\frac{1}{SIV_2} + \frac{1}{SIV_3} + \ldots + \frac{1}{SIV_6}}$	$\dfrac{5}{\frac{1}{SIV_1} + \frac{1}{SIV_2} + \ldots + \frac{1}{SIV_5}}$	$\dfrac{7}{\frac{1}{SIV_1} + \frac{1}{SIV_2} + \ldots + \frac{1}{SIV_7}}$

[1] SIV_i refers to the model specified and does not necessarily represent the same parameter between models. For instance, saline emergent marsh SIV_1 is not equal to barrier headland SIV_1. See Table 2 for variable naming.

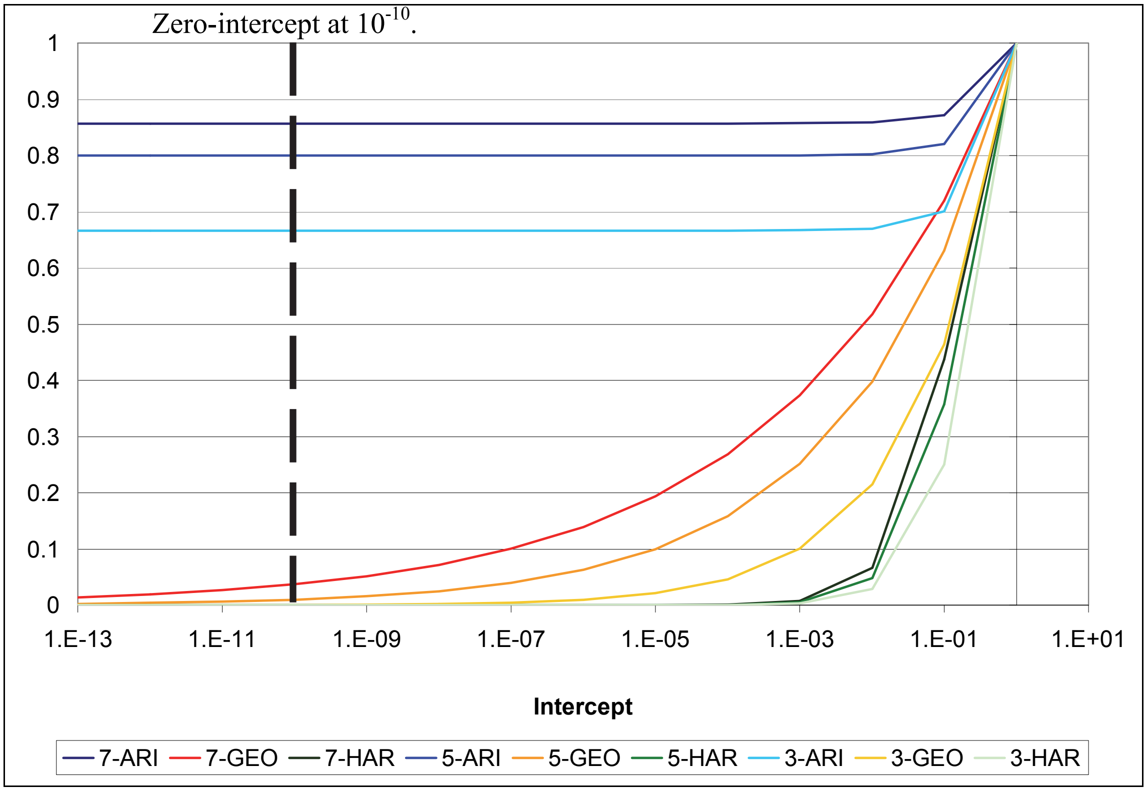

Figure 2. Combined habitat suitability indices (HSI) for "near-zero" intercepts with seven-, five-, and three-factor analyses and arithmetic (ARI), geometric (GEO), and harmonic (HAR) means.

Table 3. Test matrix.

Aggregation Technique	Non-Zero Intercept Suitability Curves	Zero Intercept Suitability Curves
WVA-specified	WVA-i	WVA-0
Geometric mean	GEO-i	GEO-0
Arithmetic mean	ARI-i	ARI-0
Harmonic mean	HAR-i	HAR-0

RESULTS: The sensitivity analysis provided important insight into the response of the WVA models relative to the two concerns expressed by reviewers, namely: (1) variation in Y-intercepts for suitability curves and (2) the method for aggregating suitability indices. Table 4 presents net average annual habitat units (AAHUs) for each of the intercept and aggregation scenarios described above. Table 5 summarizes these differences as the percent change in net AAHUs for changes in both intercept and aggregation technique. In terms of the overall magnitude of computed AAHUs, the WVA models examined were more sensitive to changes in aggregation method (average change in model results of 15.8%) than adjustments to the Y-intercepts of the suitability curves (average change in model results of 8.7%). The individual models varied in sensitivity; the saline direct model was the most sensitive to change and the barrier headland the least.

Table 4. Net average annual habitat units (AAHUs) for each alternative under multiple intercept and aggregation scenarios.

Model	Alternative	WVA-i	GEO-i	ARI-i	HAR-i	WVA-0	GEO-0	ARI-0	HAR-0
Saline Direct	Alt5	52.6	92.7	81.5	101.8	92.6	107.8	86.2	106.4
	Alt6	166.3	229.4	215.3	238.4	203.3	234.5	218.7	225.3
	Alt7	158.2	222.2	207.7	231.4	194.0	224.2	210.4	216.5
	Alt9	275.6	333.2	322.0	337.8	308.4	329.0	324.0	323.5
Saline Indirect	Alt5	52.3	61.5	69.0	53.8	59.5	53.0	70.0	47.8
	Alt6	94.6	107.0	109.2	101.2	109.3	112.3	110.5	100.1
	Alt7	46.4	52.0	52.7	49.5	61.2	56.1	54.9	53.9
	Alt9	75.0	64.6	71.4	50.2	95.1	84.9	73.8	65.4
Barrier Headland	Alt5	163.9	145.9	168.7	123.5	157.3	139.5	162.1	119.7
	Alt6	324.9	288.6	335.3	231.7	316.8	283.8	327.2	230.6
	Alt7	418.6	358.4	434.2	265.4	405.5	348.4	421.0	261.2
	Alt9	401.8	327.2	423.4	211.1	384.7	314.1	406.5	206.7
Barrier Island	Alt1_East	248.1	233.2	245.9	213.6	247.9	183.2	245.2	178.8
	Alt1_West	54.9	45.5	55.7	35.4	52.6	22.2	53.3	17.7
	Alt2_East	460.6	464.3	458.1	459.0	466.6	468.8	463.9	462.8
	Alt2_West	212.4	211.9	212.2	210.1	212.1	214.4	211.9	209.7
	Alt3	523.2	501.9	517.7	461.0	525.8	431.5	519.5	405.1
	Alt5	730.9	735.8	727.1	732.8	737.1	764.8	733.0	746.9

Table 5. Percent change in Net AAHUs.

	Change in Intercept			Change in Aggregation		
Model	**Avg**	**Min**	**Max**	**Avg**	**Min**	**Max**
Saline Direct	11.5	0.6	76.0	26.6	4.9	93.5
Saline Indirect	13.0	1.1	31.9	13.6	0.1	33.1
Barrier Headland	3.0	0.5	4.4	17.1	2.9	47.5
Barrier Island	7.8	0.1	51.2	9.1	0.1	66.3
All Models	8.7	0.1	76.0	15.8	0.1	93.5

While the absolute value of these changes might be considered large, in relative terms they're virtually inconsequential. Figure 3 presents the relative rankings of each alternative for each sensitivity analysis scenario. Of 144 possible rankings, only 20 were changed as a result of the eight intercept/aggregation combinations. **In no case was the highest scoring alternative replaced by another alternative as a consequence of the adjustments to intercept or to aggregation method.**

DISCUSSION: This analysis provides insight into the sensitivity of the models relative to the two conditions highlighted by model reviewers (BMI 2009). **The combined effects of the two response variables can affect the absolute magnitude of the output from the models, but they do not meaningfully affect the relative ranking of the alternatives.** Consequently, the model sensitivity analysis allowed the project team to respond to review comments as follows:

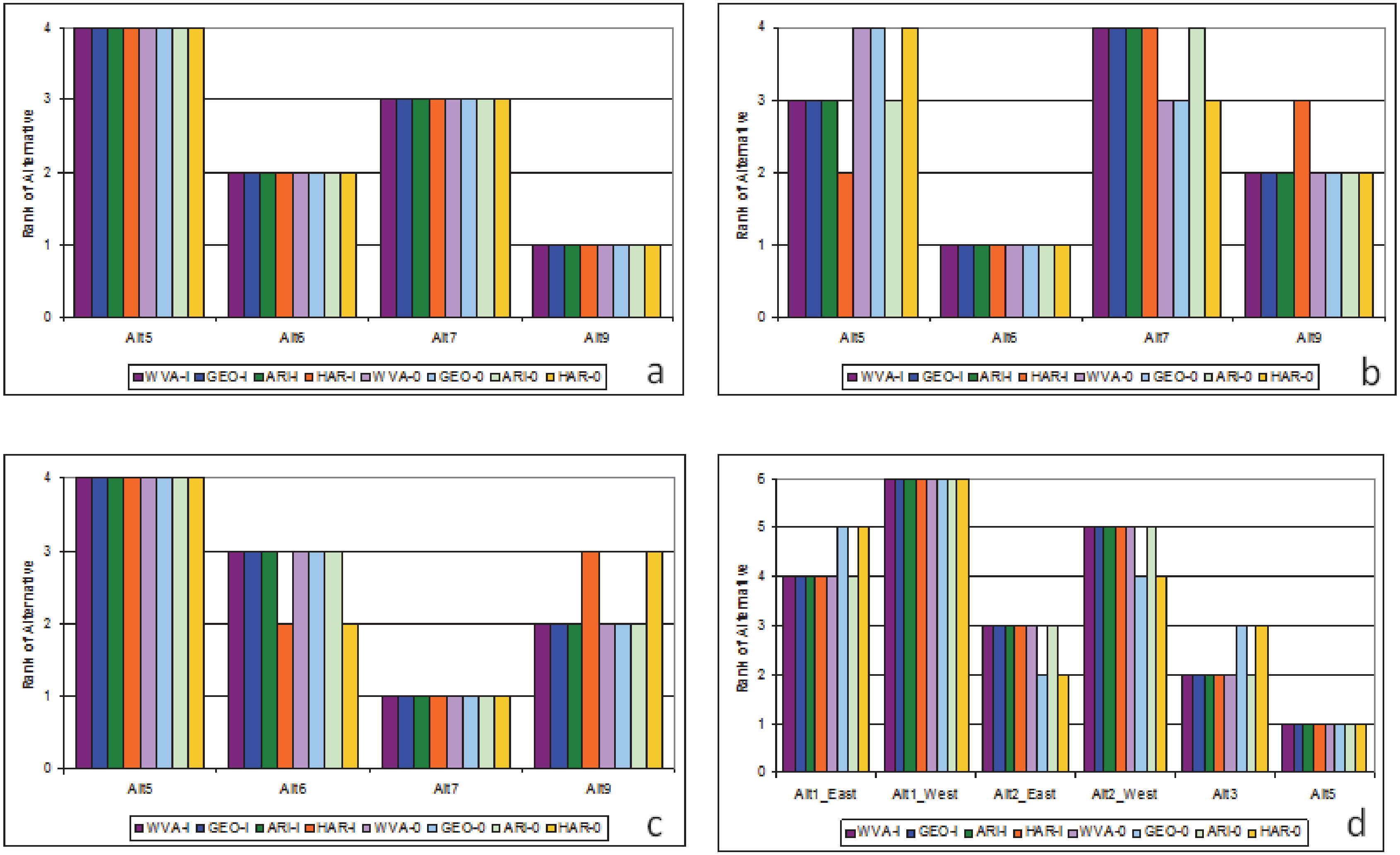

Figure 3. Relative rank of alternatives under different sensitivity scenarios (Refer to Table 3 for naming system) for each WVA model: (a) saline direct; (b) saline indirect; (c) barrier headlands; and (d) barrier islands.

Comment 1. Starting the SI curves for all variables at 0.1 is problematic because even habitat with no ecological value appears to have some ecological value.

This analysis shows that, for the BBBS study, application of zero-intercept suitability curves would not affect the relative rankings of project alternatives and has limited effect on the computed outputs. Given the relative and absolute magnitude of the changes, it appears unlikely that changing to a zero intercept would affect decisions. Furthermore, because model developers established the ecological basis for non-zero intercepts in the WVA model and given the lack of a strict requirement for a zero-slope intercept in community HEP models, the authors support the use of non-zero intercepts in WVA model applications.

Comment 18. The use of the geometric mean may be more appropriate than the arithmetic mean to derive some HSIs. Provide scientific basis for the decision to use one over the other.

The authors disagree with the reviewers' comment. The basis for the comment appears to be a presumption that there might be limiting factors for habitat best addressed through geometric averaging. For community-based models, it is not clear that there is an ecological basis for this assumption. Furthermore, sensitivity analysis shows that, while applying geometric averaging as well as other aggregation schemes that accomplish the same aim may change the overall magnitude of the output, it does not affect the relative ranking of alternatives in the case of the BBBS study.

CONCLUSIONS: Regardless of purpose or function, all models are limited by scientific understanding of the process being modeled, validity of input parameters, and ability of the model structure to capture understood processes. As shown here, there is value in examining model sensitivity to changes in one or all of these factors and how that sensitivity alters conclusions drawn from model results. While the authors recommend moving beyond sensitivity analysis and suggest accounting for uncertainty explicitly, simple sensitivity analyses like those shown here are helpful in almost any model application.

SYMBOLS:

AAHU	Average Annual Habitat Unit
BBBS	Barataria Basin Barrier Shoreline
BMI	Battelle Memorial Institute
EBA	Environmental Benefits Analysis
ERDC	U.S. Army Engineer Research and Development Center
EWG	Environmental Working Group
HEP	Habitat Evaluation Procedures
HSI	Habitat Suitability Index
HU	Habitat Unit
IEPR	Independent External Peer Review
LCA	Louisiana Coastal Area
SIV	Suitability index value
USACE	U.S. Army Corps of Engineers
USFWS	U.S. Fish and Wildlife Service
WVA	Wetland Value Assessment

ADDITIONAL INFORMATION: Research presented in this technical note was developed under the Environmental Benefits Analysis (EBA) Research Program. The USACE Proponent for the EBA Program is Ms. Rennie Sherman, and the Technical Director is Dr. Al Cofrancesco. Publication of this case study was at the request of Shawn Komlos (USACE Institute for Water Resources) and Jodi Staebell (Ecosystem Restoration Planning Center of Expertise). Permission to publish this analysis was provided by Fay Lachney and Bill Klein (USACE New Orleans District). Technical reviews by Drs. Bruce A. Pruitt and Burton Suedel are appreciated.

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